Comparison of Interpolation Algorithms for Digital Elevation Model Generation and Subsequent Viewshed Analysis

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Abstract. Models created by geographic information systems are becoming increasingly important tools for the management of natural and cultural resources. These models, however, are only as good as the algorithms used to create them. We examine the effects of four different algorithms on digital elevation models (DEM's) and on the viewshed analyses derived from these models. Each algorithm will create a unique DEM from the same data set; each algorithm has weak points; and the choice of algorithms has important consequences for the accuracy of both the resulting DEM and the viewshed based on the chosen model. Each interpolation algorithm, given identical data sets, will create a unique DEM, and there are often important differences between the different DEM's. We can infer from these differ-

ences that there will never be a one-to-one correspondence between DEM's and the real world as long as interpolation algorithms are used. Differences in DEM's will affect derived themes like viewshed analysis—sometimes significantly.

Key words: Algorithm, digital elevation model, error evaluation, geographic information systems, viewshed analysis.

As the modeling capabilities of geographical information systems (GIS) increases and the gap between the real world and computer-generated models shrinks, we must acknowledge a difference between the real world and the models of the real world that we create. The growing sophistication of GIS software has created a powerful tool for managing natural and cultural resources, which makes it easy to view the real world and the image that appears on our computer monitor as parallel realities. In truth, the accuracy of the image on the monitor is only as good as the equations used to create it. To demonstrate the effects of different equations on model results, we examine four algorithms used to interpolate digital elevation models (DEM's) and the effects of these algorithms on viewshed analysis in the Tonto National Monument.

Study Area: Tonto National Monument

We combined efforts at the University of Arizona at Tucson—between the National Park Service (Cooperative Park Service Unit, University of Arizona), Advanced Resource Technology program (ART) in the School of Renewable Natural Resources, and the Arizona State Museum—to create GIS-compatible data bases for several of the National Park units in Arizona. We chose Tonto National Monument on the shores of Theodore Roosevelt Lake, about 97 km east of Phoenix, Arizona, to use as an example in this paper. The monument is known primarily for its spectacular examples of Sinagua cliff dwellings. Because of its proximity to Phoenix and the large reservoir, a major concern at the monument is how increased development around the lake will affect the resources and prehistoric setting of the monument. Our principle objective at Tonto was to evaluate the visual effects of recreational camp sites and other development on the prehistoric viewshed.

Digitizing Contours for Interpolation

The data for Tonto National Monument were digitized using a Calcomp 9500 digitizing tablet and the AutoCAD release 10.0 (Autodesk 1989), a computer-aided drafting package. Two basic themes, elevation data and features of interest, were digitized for Tonto National Monument. The features of interest included the monument boundary, roads, trails, buildings, and cliff dwellings. For our purposes, elevations were digitized at two different intervals (40-foot and 200-foot contours).

Software Used in the Analysis

IDRISI

Once digitized, the basic vector themes of elevation data and features of interest were transferred to the IDRISI GIS software package, developed by the Clark University Graduate School of Geography (Eastman 1990). The vectors were converted to a raster format, with 50-m cells, and additional themes were generated from them using the IDRISI modules. The themes generated included a DEM, slope and aspect data, and a viewshed analysis.

Terrain Pac

For our paper, the IDRISI contour data were also exported to a software package called Terrain Pac. This set of programs was developed by Kenneth L. Kvamme (University of Arizona Department of Anthropology and the Arizona State Museum) to work directly with IDRISI's GIS software. As the name suggests, the primary emphasis of Terrain Pac is in terrain analysis. Four different algorithms for interpolating DEM's, as well as algorithms for determining slope, aspect, ridge/drainage index, local relief, and rim index are included.

Creating Digital Elevation Models

Digital elevation models are created by algorithms that determine elevation values for each cell in a raster grid by interpolating them from known elevations. The known elevations are generally in rasterized contours digitized from topographical maps. The value of a DEM is dependent on the accuracy and comprehensiveness of the digitizing and on the sophistication and suitability of the particular algorithm used in its creation.

Algorithms Used for the Creation of Digital Elevation Models

There are several different algorithms used for the creation of DEM's, and the particular algorithm chosen by the researcher or, more likely, the choice that has been made for him by the programmers of the software he is using, is important in determining the accuracy of the images that will be created. The Terrain Pac DEM creation module currently supports four different algorithms: linear by row, linear by column, eight-direction linear, and eight-direction weighted average. Using the same data set, each algorithm was used to interpolate DEM's for the area of Tonto National Monument. These models were then smoothed and exported to IDRISI for analysis.

Linear by Row Algorithm

Linear by row algorithms search left and right along the row in which each cell of unknown elevation is located until known elevations are encountered in each direction of search. Based on these two cells of known elevation, the algorithm interpolates an elevation value for the cell in question. The nature of this simple algorithm tends to produce a terraced effect, creating ridges along the rows of the grid. This terracing can be quite dramatic when a DEM is examined closely.

Linear by Column Algorithm

Linear by column algorithms are essentially identical to linear by row algorithms, except that they search up and down by column. Because this algorithm searches along columns, rather than along rows, the terraced effect is found in ridges forming along the columns of the raster grid.

Eight-direction Linear Algorithm

The eight-direction linear algorithm searches left and right along the row, up and down along the column, and outward along each diagonal until four pairs of known elevation are encountered. Based on the difference between the two known elevations in each pair, the algorithm determines the direction of steepest slope and interpolates an elevation value for the cell based on this pair. Because each cell of unknown value can be interpolated along any of four axes, the tendency toward terracing seen in the two-direction linear algorithms discussed above is substantially reduced. On the other hand, this algorithm often has problems in interpolating flat surfaces, creating low ridges and shallow valleys where none exist. For example, in the Tonto National Monument study area, this algorithm interpolated low ridge lines onto the surface of Theodore Roosevelt Lake.

Eight-direction Weighted Average Algorithm

This algorithm uses the same search pattern as the eight-direction linear algorithm, but the value interpolated for cells of unknown value is based on an average of the eight known elevations weighted by the reciprocal of the Euclidean distance. The effect is one of rounding or smoothing of the terrain, and at times this algorithm will interpolate concave scallops onto slopes.

Tonto National Monument Digital Elevation Models

Although sometimes difficult to discern from a computer monitor, the differences between DEM's created by the different algorithms are real and can affect analysis. In the study region around Tonto National Monument, for example, these differences are not noticeable to the naked eye; but one DEM subtracted from another on a cell by cell basis exposes significant differences between the two DEM's. If the two DEM's are identical, the resultant image will consist entirely of zeros. As differences between the two increase, the number of cells with values other than zero, along with the range of values, will also increase.

When the DEM's from the study area were subtracted, differences between the images became readily apparent. These derived images feature variation in height and depth, especially in the more mountainous areas. While cells in these images clustered around zero values, there were significant numbers of cells with values other than zero. As an example, when the DEM created by the linear by row algorithm is subtracted from the DEM created by the linear by column algorithm, the resulting image has values between –1 and 1 foot in 47% of its cells and values ranging from –200 to 161 feet (Table 1). Obviously, then, there was a significant number of cell values that differed between the two DEM's, and these differences were as much as 200 feet in a given cell. It would be expected that DEM's created by the eight-direction linear and the eight-direction weighted average algorithms would have a greater similarity, and this is the case. Subtracting the DEM's created by these algorithms still yields an image with only 48% of its cells between –1 and 1 foot but with a significantly smaller range in the cell values, between –100 and 94 feet.

The effects of this can be further mitigated by digitizing contour data at smaller intervals or, correspondingly, if you have larger contour intervals you can increase your cell size to reduce the variability in interpolation. When DEM's of this same area are based on 40-foot contours, the results gained by subtracting the images are less dramatic in all cases (Table 2), with an increase in the cells clustering around zero and a decrease in the range of values other than zero. The minimum and maximum numbers in Table 2 are somewhat misleading. Because we are using 40-foot contour intervals, the range should be between –40 and 40. Values outside this range are single, rogue cells, reflecting holes in the digitizing. In an area as large as that covered by this study, gaps in the digitized data are inevitable even under

Table 1. Differences between digital elevation models (DEM's) using 200-foot contours.

DEM interpolation algorithms	Minimum difference (feet)	Maximum difference (feet)	Cells between –1 and 1 foot (%)
L-R minus L-C[a]	–200	161	47
L-R minus 8-L	–141	154	49
L-R minus 8-W	–150	133	50
L-C minus 8-L	–134	155	59
L-C minus 8-W	–99	117	51
8-L minus 8-W	–100	94	48

[a] L-R = linear by row; L-C = linear by column; 8-L = 8-direction linear; 8-W = 8-direction weighted average.

most carefully controlled digitizing. In actuality, there is considerably less variability in the DEM's than is evidenced by the minimum and maximum values in Table 2. The images resulting from this subtraction are also substantially different in form—the mountainous regions have been reduced to flat plains while flat regions show greater variation. This reflects the fact that the digitized lines in the mountainous regions are closer together, reducing the number of cells that need to be interpolated and thereby reducing the variability between the different DEM's.

Digital Elevation Models and Viewshed Analysis

The obvious conclusion to be drawn from the above analysis is that given the same set of contours, each interpolation algorithm will create a unique DEM. It is important, then, to understand both the effects of the interpolation algorithm on the DEM and how this will, in turn, affect the products derived from the DEM. Themes—such as viewshed, slope, and aspect—will all be affected by the interpolation algorithm used because these data sets are products of the DEM. For our purposes, simple viewshed analyses were carried out on the four DEM's of Tonto National Monument.

Creating Viewsheds

Creating a viewshed model is a relatively simple process for a computer. The computer simply calculates, based on distance and elevation, all cells visible from one or more viewpoint cells situated on the surface of a DEM. For our study area, the viewpoint chosen was the Upper Ruin in Tonto National Monument, located on a generally east-facing slope. As we have seen, DEM interpolation algorithms by their very nature tend to overvalue elevation at certain points and undervalue it at others. Obviously, differences in these valuations from one algorithm to the next can lead to dramatic differences in viewshed analyses.

Table 2. Differences between digital elevation models (DEM's) using 40-foot contours.

DEM interpolation algorithms	Minimum difference (feet)	Maximum difference (feet)	Cells between 1 and 1 foot (%)
L-R minus L-C[a]	–71	46	55
L-R minus 8-L	–97	39	50
L-R minus 8-W	–49	33	59
L-C minus 8-L	–82	43	56
L-C minus 8-W	–34	47	57
8-L minus 8-W	–31	67	52

[a] L-R = linear by row; L-C = linear by column; 8-L = 8-direction linear; 8-W = 8-direction weighted average.

Tonto National Monument Viewsheds

Because the general direction of view from the Upper Ruin at Tonto National Monument is toward the east, the effect of interpolation algorithms on viewshed analysis was most clearly seen in the viewshed based on the DEM interpolated by the linear by column algorithm. This algorithm created ridges oriented on a north–south axis, leaving significant blind spots in the viewshed that are not present in viewsheds based on the other DEM interpolations.

Each of the four DEM interpolation algorithms created a unique viewshed. To discover these differences, each of the viewshed images were subtracted from the other viewsheds, creating images that detailed the areas in common as well as those unique to each. To further highlight these differences, the area that was out of view in all viewsheds (i.e., the area behind the mountain) as well as the flat surface of the lake were not included in the analysis. The difference was greatest between those viewsheds based on the linear by row and linear by column DEM's, with only 83% of the in-view cells common to both, while the viewshed analyses that were most similar had 93% of the cells in common (Table 3).

Differences between viewsheds decrease when they are based on DEM's interpolated from 40-foot contours. Viewshed images based on these DEM's tend to be more complex and less uniform. Cells in view and out of view tend to form smaller, less contiguous areas in reflection of the greater variation of the DEM surface. Additionally, the differences between viewsheds derived from different DEM's are less. None of the areas common to both viewsheds is less than 90% (Table 4). Once again, this indicates the importance of digitizing as many contour lines as possible.

Conclusions and Suggestions

Based on the preceding analysis, it is possible to draw several conclusions:

1. Each interpolation algorithm, given identical data sets, will create a unique DEM;

Table 3. The effect of interpolation algorithms on viewsheds using 200-foot contours.

DEM interpolation algorithms	Common to both (%)	In viewshed A only (%)	In viewshed B only (%)
L-R (A) minus L-C (B)[a]	83	15	2
L-R (A) minus 8-L (B)	86	13	1
L-R (A) minus 8-W (B)	93	6	1
L-C (A) minus 8-L (B)	91	4	5
L-C (A) minus 8-W (B)	89	1	10
8-L (A) minus 8-W (B)	91	1	8

[a] L-R = Linear by row; L-C = Linear by column; 8-L = 8-direction linear; 8-W = 8-direction weighted average.

Table 4. The effect of interpolation algorithms on viewsheds using 40-foot contours.

DEM interpolation algorithms	Common to both (%)	In viewshed A only (%)	In viewshed B only (%)
L-R (A) minus L-C (B)[a]	91	8	1
L-R (A) minus 8-L (B)	94	5	1
L-R (A) minus 8-W (B)	96	3	1
L-C (A) minus 8-L (B)	92	2	6
L-C (A) minus 8-W (B)	94	1	5
8-L (A) minus 8-W (B)	95	2	3

[a] L-R = Linear by row; L-C = Linear by column; 8-L = 8-direction linear; 8-W = 8-direction weighted average.

2. There are often significant differences between these different DEM's;
3. We can infer from these differences that there will never be a one-to-one correspondence between DEM's and the real world as long as interpolation algorithms are used; and
4. Differences in DEM's will affect derived themes, such as viewshed analysis—sometimes significantly. (This would become especially significant when the derived themes are those commonly used in such high-risk analyses as fire-behavior modeling.)

Based on these conclusions, we offer the following suggestions:

1. Buyer beware! Don't purchase or use DEM's or interpolation algorithms until you know what they are and how they operate;
2. Select algorithms that match the needs of your project and whose strengths match the topography of your study area. Ideally, a different algorithm should be developed for each project area, but because this is impractical in the real world, having more than one available for use will allow for a comparison of results. Don't assume total reliability from the interpolation algorithm supplied with your GIS software;
3. When digitizing contours, digitize as many contours as is physically possible; and
4. Always compare DEM's and the products derived from them to the real world.

Literature Cited

Autodesk Inc. 1989. AutoCAD 10.0. Sausalito, Calif. Not paginated.
Eastman, R. J. 1990. IDRISI 3.2. Clark University, Worcester, Mass. Not paginated.